Characterization of Clay Bricks Surface Deformation Behavior through Digital Image Analysis

David N Githinji* Charles K Nzila, Diana S Madara and John T Githaiga

Department of Manufacturing, Industrial & Textile Engineering, Moi University, P.O. Box 3900-30100, Eldoret, Kenya

Abstract

Handmade compacted clay bricks are an important integral building material especially for the low cost durable and affordable housing segment. Characterisation of physical, mechanical and deformation behavior of handmade clay bricks is essential to ensure material integrity and durability. In this paper, physical and mechanical properties are determined and the Particle Image Velocimetry (PIV) method is used to assess deformation behavior of bricks under uniaxial compressive loading. The bricks exhibit brittle failure with high strain localized along the cracks. The initiation and development of cracks on loading redistribute compressive strain within the brick with some regions experiencing minimum strain at failure. The relatively large displacements between cracks account for relatively large failure strain for the brittle bricks. A good concurrence is established between the strain assessment based on uniaxial compressive test and on image correlation using the PIV method. The average vector magnitude derived from PIV measurements, correlate well with the engineering strain and can thus be used for strain estimation in handmade clay bricks.

Keywords: clay brick, Digital Image Correlation, deformation, particle image velocimetry, characterisation.

Introduction

Clay is a natural material composed mainly of crystalline minerals which are essentially hydrous aluminium silicates with small quantities of iron or magnesium replacing aluminium partly or wholly in some minerals (Murthy, 2002). Clay may also contain water-soluble minerals and organic material as discrete particles or as organic molecules adsorbed on clay minerals. Moist clay material exhibits plasticity and upon drying a rigid structure is formed. The clay mineral in the structure decomposes into free alumina, free silica and water vapour on heating. On further heating, a liquid glass is formed from some of these free oxides, alkalis and other fluxes in the clay material, which crystallizes into mullite at temperatures above 1200°C. The constituents of clay bricks therefore include mullite crystals, silica and a glassy matrix with minor constituents of unaltered quartz, free alumina, calcium and other silicates (Engineers, 2007). As a natural material, clay has varying chemical composition depending on changes in the environment where clay deposits are found. Consequently, the mechanical and physical properties of clay bricks vary on a regional level. Characterization of clay bricks is therefore relevant to understand their physical and/or mechanical properties so as to evaluate their safety in load bearing structural applications. Most studies on the characterisation of clay brick focuses on their ageing process, durability, thermal properties, physical properties and mechanical properties (Baronio & Binda, 1984; Baronio & Binda, 1985; Dondi, et al., 1999; Elert, et al., 2003; Sedat, et al., 2006)

Information about characterisation of clay brick deformation behavior using digital image analysis is rather scarce. Digital image correlation has been applied to study fracture toughness of clay brick (Lorenzo, et al., 2014) and strain measurements of large masonry walls (Salmanpour & Mojsilovic, 2013). This paper aims at applying the digital image correlation method to assess the surface deformation behavior of clay bricks. The Particle Image Velocimetry (PIV) plug-in installed in the ImageJ software (Abramoff, et al., 2004) is used. PIV is a displacement measuring technique of small particles embedded in a region of a fluid. The theory, working principle and applications of PIV are expounded in several studies (Willert & Gharib, 1991; Westerweel, 1993; Willert, 1996; Westerweel, 1997; Westerweel, 2000). The method works by recording at different times, the light reflection from tracer particles in a flowing medium, thus allowing evaluation of their displacement. A typical PIV setup consists of a digital camera, light source and image analysis software. For accurate PIV assessment, the camera setting and lighting are maintained constant during the measurement. The particle movement from one point to another is quantified in using vector magnitude. The PIV method has been applied previously (Githinji, et al., 2015) in strain assessment in other materials. The main advantage of this method is that a freeware is used making it more accessible and relatively cheap.

In the current study, a clay brick was first characterized to determine its bulk density, porosity, water absorption, loss of ignition, compressive and flexural strength before deforming it in compression at a constant rate of loading. The elemental displacement of surface particles during loading was tracked using digital images and analysis performed using the PIV method. The PIV analysis enabled both qualitative and quantitative assessment of damage evolution and strain distribution in the clay brick to be determined as a function of compressive loading. The findings of the current work will be of great importance in structural integrity assessment of loaded clay brick structures.

Materials and Methods

Materials

The clay bricks adopted in this study were handmade and were collected from the same ecological zone. On average, the bricks were about 250 mm in length, 120 mm in width and 100mm in height. At least ten clay brick units were randomly selected and used in the current study.

Methods

Characterisation of physical properties

The average density of the clay bricks was computed from their average mass and average volume. The measurement of dimensions was in accordance with Kenya Standard KS EAS 54:1999 (KeBS, 1999). The total porosity volume was computed from the weight gain of oven dried clay bricks saturated with boiling water (Duggal, 2009). The void volume fraction was given by the ratio of the volume of water absorbed to the volume of saturated clay bricks. The determination of water absorption was in accordance with the test method specified in Kenya Standard KS EAS 54: 1999.

Characterisation of chemical properties

Determination of loss of ignition (LOI) was based on 0.5g of finely ground clay sample which was oven dried for 4 hours at 250°C followed by cooling in a desiccator and re-weighing. The LOI was given as the percentage weight loss.

Characterisation of mechanical properties

The compressive strength of the bricks was determined in accordance with Kenya Standard KS EAS 54: 1999. The dry compressive tests were conducted on a Uniaxial Testing machine. The tests were performed in displacement controlled mode at a constant rate of 2.5 mm/min crosshead speed on specimens measuring 30 mm x 30 mm x 50 mm machined in the moulding direction from the collected brick samples. The specimen height/width ratio was more than 1.5 which was adequate for minimizing the boundary effect. The compressive strength was calculated by dividing the peak compressive load by the original cross-sectional area of the brick specimen. The compressive strain was computed from the specimens' dimensions and the machine displacements.

The flexural rigidity test was performed on a Uniaxial Testing machine following a 3-point bending test on brick specimens measuring 200 mm in length, 140 mm in width and 60 mm in height. The flexural rigidity was calculated from the maximum load applied before failure and the dimensions of the specimen. The mechanical tests were not conducted on the whole brick specimens owing to the limitation of the testing machine and also to avoid the effects of the brick's edge material.

Characterisation of brick's surface deformation behavior

A digital camera (Nikon D3100 14.2 MP with 18-55 mm VR Lens) was used to capture sequential images of the brick specimen during the compressive tests. For every 0.5 mm compression of the specimen, an image was captured and this was repeated until the specimen failed. A total of five compression tests were conducted and only average values are reported in this paper. ImageJ software installed with a PIV plugin was used to qualitatively analyze the uniformity of surface deformation, using vector magnitude maps. This was achieved by correlating a zero strained image with an image captured under various strain conditions. The strain built-up, after each 0.5 mm compression interval, was quantified by averaging the vector magnitudes of the displacements of all elements in the camera field of view.

Results and Discussion

Characterisation of bricks properties

The experimental results are given in Table 1. These results include average values of void fractions, water absorptions, bulk densities, compressive strength, flexural strength and loss of ignition.

Table 1: Characterized properties of clay bricks studied.

Void fraction	% water absorption	Bulk density (kg/m^3)	Compressive strength (MPa)	Flexural Strength (MPa)	LOI (%)
0.27	38	1715	2.5	0.30	2

The determined void volume fraction value of 0.27 was found to be within the nominal range (0.01 - 0.5) for clay bricks as reported by other researchers (Engineers, 2007) (Phonphuak, 2013) for clay bricks. A relatively high water absorption value of 38% obtained for the brick samples may be attributed to the void volume fraction which provided space for water during the immersion tests. Moreover, this value is within the range (20-40%) reported in literature (Cobb, 2008) for similar clay bricks. The bricks have a good bulk density since the determined quantity (1715 kg/m^3) was within the typical range (1600 - 1800 kg/m^3) for clay bricks previously reported (Duggal, 2009), which mainly depends on clay composition and void volume fraction (Phonphuak, 2013). For the determined brick compressive strength of 2.5MPa, a closely correspondence to that specified in the KS EAS 54:1999 Standard for internal clay bricks was established. The brick's relatively low strength value despite its relatively high bulk density may be attributed to inadequate fusion between clay minerals owing to factors such as low curing temperature and the presence of a large proportion of non-fusing impurities in the clay material. It is also possible that the clay bricks tested had lines of weakness owing to agglomeration of voids in the structure, which may explain, why crack initiation and development originated along specific areas of the brick (see Fig. 2). The LOI value obtained could be related to the presence of organic material in the clay material which decomposed on high temperature heating. Since the physical and mechanical properties reported in this paper for the clay brick correspond to those in published literature, its deformation behavior may be a fair representation of this category of building material.

The installed software in the Universal Testing Machine, allows for the results to be presented in various formats. The nature of the failure and related stress-strain behavior is continuously computed during the compression loading cycle. Fig. 1 shows the engineering stress-strain curve for a clay brick sample load in compression. Similar curves were obtained from the five compression tests conducted. From the results, it is clear that the failure occurred in a brittle manner with negligible plastic strain. This behavior could be attributed to the strong bonding between clay particles (e.g. various oxides of Si, Ca, Ti, Al) after high temperature curing resulting in rigid structures. The accumulated compressive strain on loading can be attributed to relative displacement between different parts of cracked brick. Since the brick is brittle in nature, this compressive strain is accommodated by the brick's lateral spread which leads to crack widening with increasing strain (Fig. 2d). The stress-strain curve's nonlinearity can be attributed to occasional slight reduction in load bearing capacity of the brick owing to cracking with the subsequent increase in load bearing arising from redistribution of stress in the structure upon further compression.

The flexural strength of the clay brick was only about 10% of its compressive strength which may indicate relatively low shear strength of the bricks. Similar flexural strength values have been reported previously (Cobb, 2008) for similar clay bricks.

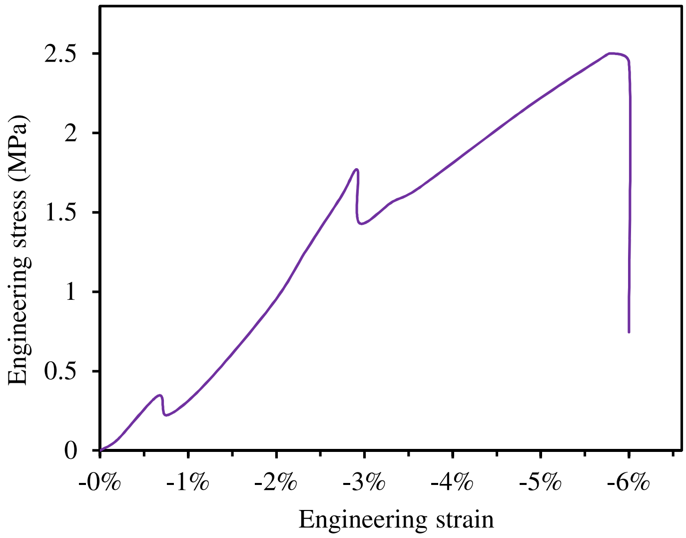

Fig. 1. A sample of compressive stress-strain curve for clay brick sample loaded to failure.

Characterisation of Bricks Deformation Behavior

The results of the deformation behavior of the bricks through image measurements and analysis are presented. Fig. 2 shows sequential macro-images of the specimens' side-view taken at an engineering compressive strain of 0%, 0.5%, 2.5% and 5.8% and their corresponding vector magnitude (displacement) maps. Failure of the specimen occurred after 5% engineering strain and was characterized by large macro-cracks. The vector magnitude maps were obtained by correlating the image captured at 0% strain with those captured at higher engineering strains. The degree of displacement of surface elements as tracked progressively from their original positions is represented by a rainbow coloring scale. The blue colour indicates the least displacement while the red colour designates the maximum displacement of surface elements as a function of the applied strain.

It is evident that the surface displacement progressed along certain regions of the brick surface, where cracks initiated and developed as loading was increased. From Fig. 2(b), it is clear that the PIV method can be used to detect crack initiation points in clay bricks under compressive loading. As seen in Fig. 2(c), maximum displacement was localized around the cracking regions while the other regions had limited displacement. This may be attributed to relative movement between brick's layers separated by a crack. The measured compressive strains could therefore be attributed to this displacement rather than to the plastic deformation of the brittle brick. Apparently, at relatively high strains, the displacement on the surface occurred also at other parts of the brick (Fig. 2d) which may be due to limited displacement along the cracked region. This displacement may have contributed to initiation and development of new cracks in these parts of the brick, resulting to its ultimate failure at about 5.8% engineering strain. Apparently, some regions of the brick surface (see area marked with X in Fig. 2d) experienced minimal displacement even at the point of failure. This may be attributed to the brittle nature of the brick material which may have inhibited uniform load transfer to all parts of the brick separated by macro-cracks. This underpins the importance of avoiding crack development in clay bricks used as structural material in load bearing applications.

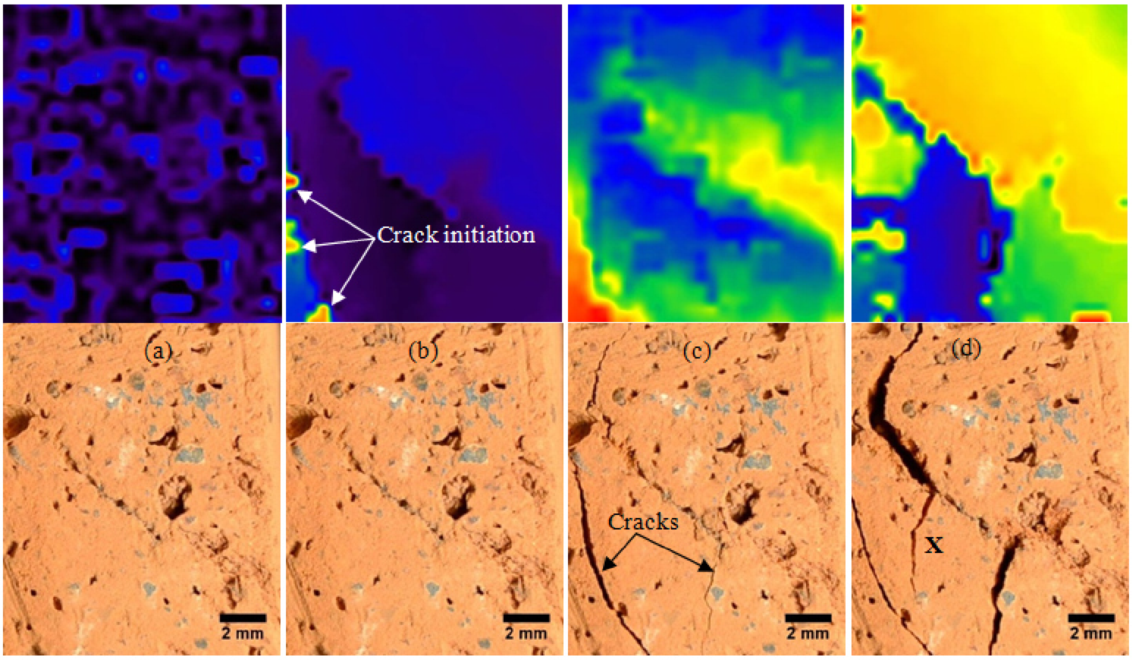

Fig. 2. Macrographs and their corresponding vector magnitude maps for clay brick with: (a) 0%, (b) 0.5%, (c) 2.5% and (d) 5.8% engineering strains. Rainbow colour coding from blue to red represent minimum to maximum strains in the structure. Part marked X has minimum strain.

Fig. 3 shows the variation of average vector magnitude with the engineering strain. The error bars in the curve represents the standard error in the measured average vector magnitude and it is assumed that the error in strains measurement was negligible. A rapid increase in vector magnitude occurs for strains less than 1% after which the rate of increment reduces. This could be due to relatively uniform displacement distribution at strains less than 1% (Fig. 2b) yielding a relatively high average vector value. The flattening of curve between 0.5% and 2.5% strains may be ascribed to localized displacement along the cracking regions (Fig. 2c) leading to a decrease in average vector magnitude per unit strain. For strains more than 2.5%, the redistribution of displacements in other parts of the brick (Fig. 2d) leads to an increase in average vector magnitude per unit strain. Apparently, the PIV method can be used to assess the state of deformation of clay brick under compressive loading if its initial state is digitized in an image. The accumulated strains in the structure may thus be estimated from properly developed calibration curves of vector magnitude versus strain.

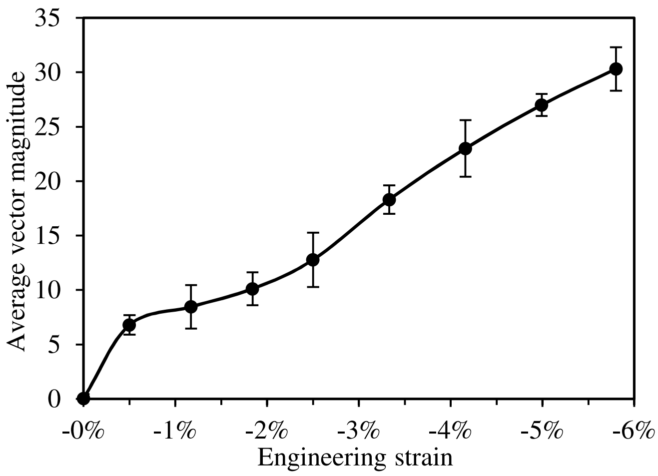

Fig. 3. Variation of average vector magnitude with engineering strain obtained from clay brick.

Conclusion

In the current study, handmade clay bricks collected from the same ecological zone are characterized in terms of their physical, mechanical, and chemical properties. The bricks surface deformation behavior is evaluated using the PIV method and the following conclusions are drawn from the study:

- The determined physical properties (void fraction, bulk density, and water absorption) and mechanical properties (compressive and flexural strength) of the clay bricks in this work, agree well with the results reported in literature and hence the samples are a fair representative of this type of building material.
- The stress-strain curve of the clay bricks exhibits brittle failure, thought to be as result of strong bonding between clay particles on high temperature firing.
- Detection of crack initiation points in clay bricks under compressive loading is possible using PIV method.
- Strain accumulation under compressive loading in clay bricks arises from relative displacement between regions separated cracks as they laterally spread under load.
- The stress distribution in a cracked clay brick is not uniform which is thought to be as result of brittle nature of the fired brick material, fissures in the structure and non-uniformity in material hardness.
- Digital image correlation using the PIV method gives both qualitative and quantitative assessment of deformation in clay bricks. The average vector magnitude derived from the PIV measurements, correlate well with the engineering strain and can thus be used for strain estimation in similar structures.

Acknowledgement

The authors would like to thank Mr. Osiemo AO and Ayoro PO for their assistance in collection of clay bricks and VLIR-OUS MU for partially funding this research.

References

Abramoff, M., Magalhaes, P. J. & Ram, S. J., 2004. Image processing with ImageJ. *Biophotonics international,* 11(7), pp. 36-42.

ASTM, 2013. *C 1072 -13E1 Standard Test Methods for Measurement of Masonry Flexural Bond Strength.* Pennsylvania: ASTM International.

Baronio, G. & Binda, L., 1984. Measurement of the resistance to deterioration of old and new bricks by means of accelerated aging tests. *Durability of building materials,* Volume 2, pp. 139-154.

Baronio, G. & Binda, L., 1985. "Physico-mechanical characteristics and durability of bricks from some monuments in Milan. *Masonry International,* Volume 4, pp. 29-35.

Cobb, F., 2008. *Structural Engineer's Pocket Book: British Standards Edition.* 2 ed. s.l.:Elsevier.

Dondi, M., Marsigli, M. & Venturi, I., 1999. Microstructure and mechanical properties of clay bricks: comparison between fast firing and traditional firing. *British Ceramic Transactions,* 98(1), pp. 12-18.

Dondi, M. et al., 2004. Thermal Conductivity of Clay Bricks. *Journal of Materials in Civil Engineering,* 16(1), pp. 8-14.

Duggal, S. K., 2009. *Building Materials.* s.l.:New Age International.

Elert, K., Cultrone, G., Navarro, C. & Pardo, S., 2003. Durability of bricks used in the conservation of historic buildings - influence of composition and microstructure. *Journal of Cultural Heritage,* Volume 2, pp. 91-99.

Engineers, N. B. o. C. &., 2007. *The Complete Technology Book on Bricks, Cement and Asbestos.* s.l.:Niir Project Consultancy Services.

Githinji, D. J.T Githaiga, D.R Tuigong, D.S Madara, B Kipsang and Khasindu S., 2015. Fabrication, Characterization and Deformation Behavior of a New Acrylate Copolymer-based Nonwoven Structure. *Chemistry and Material Research,* 7(7), pp. 11-19.

KeBS, 1999. *KS EAS 54:1999, Burnt Building Bricks - Specification,* Nairobi: Kenya Bureau of Standards.

Lorenzo, G. G, K Marcin, S Tomasz, D Marco and L Stefano., 2014. Measurement of R-curve in clay brick blocks using optical measuring technique. Volume 121-122, pp. 1-10.

Lyons, A., 2014. *Materials for Architects and Builders.* s.l.:Routledge.

Murthy, V., 2002. *Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering.* s.l.:CRC Press.

Phonphuak, N., 2013. Effects of Additive on the Physical and Thermal Conductivity of Fired Clay Brick. *Journal of Chemical Science and Technology ,* 2(1), pp. 95-99.

Salmanpour, A. & Mojsilovic, N., 2013. *Application of Digital Image Correlation for strain measurements of large masonry walls.* s.l., 5th Asia Pacific Congress On Computational Mechanics.

Sedat, K., Sabit, E. & ikmet, G., 2006. Firing temperature and firing time influence on mechanical and physical properties of clay bricks. *Journal of Scientific & Industrial Research,* Volume 65, pp. 153-159.

Westerweel, J., 1993. *Digital Particle Image Velocimetry: Theory and Application.* Delft: Delft University Press.

Westerweel, j., 1997. Fundamental of digital particle image velocimetry. *Measurement Science and Technology,* Volume 8, pp. 1379-1392.

Westerweel, J., 2000. Theoretical analysis of the measurement precision in particle image velocimetry. *Experiments in Fluids,* Volume 29, pp. 3-12.

Willert, C. E., 1996. The fully digital evaluation of photographic PIV recordings. *Applied Scientific Research,* Volume 56, pp. 79-102.

Willert, C. E. & Gharib, M., 1991. Digital Particle Image Velocimetry. *Experiments in Fluids,* Volume 10, pp. 181-193.